

FIRST VERSUS SECOND GENERATION PLANET FORMATION IN POST COMMON ENVELOPE BINARY (PCEB) PLANETARY SYSTEMS

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ABSTRACT

We examine planets orbiting post-common envelope binaries (PCEBs) from the perspective of angular momentum evolution, and conclude that the planets are more likely to be first generation (FG) planets than second generation (SG) planets. FG planets were born together with the parent stars, while SG planets form later from a SG proto-planetary disk formed by mass loss from the evolved primary star during its red giant branch (RGB) phase or asymptotic giant branch (AGB) phase. We find that in some systems the SG scenario requires that more than twenty percent of the SG proto-planetary disk mass ends in planets. Although we cannot rule out SG planet formation in these systems, this fraction of mass that ends in planets is much higher than the value commonly used in planet formation theories. On the other hand, we find that for each of the systems we can build a progenitor system composed of main-sequence binary system orbited by the appropriate planets. This can be done if the secondary star was in a resonance with the inner planet. To account for the progenitor properties we suggest that in cases where the secondary star has a mass of $\sim 0.1 - 0.2M_{\odot}$, it was formed in the same way planets are formed, i.e., from a disk.

1. INTRODUCTION

Planets have been found around post common envelope binaries (PCEBs) where the secondary is a main sequence (MS) star orbiting a compact object on a close orbit. The compact object is the core remnant of either an asymptotic giant branch (AGB) star, where it is a CO white dwarf (WD) or a NeMgO WD, or the remnant of a red giant branch (RGB) star. In the later case the compact object might be a He WD, or a horizontal branch (HB) star, i.e., an sdB or sdO star, or a CO WD remnant of a HB star. We refer to all the objects

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that are descendant of RGB stars as RGBD objects. The evolution of PCEB hosting planets is still an open area, mainly due to open questions in the common envelope (CE) evolution itself (see review by Ivanova et al. 2013).

Planets orbiting PCEBs can form together with the binary, i.e. first generation (FG) planets, or can form after the CE phase, i.e. second generation (SG) planets (Parsons et al. 2010b; Perets 2010, 2011; Schleicher & Dreizler 2014; Völschow et al. 2014). Exoplanet systems around MS binary systems with a low-mass secondary star suggest that the FG scenario is plausible. Examples include the planet Kepler-16b that orbits with a period of 228 day a stellar binary system of masses $M_1 = 0.69M_\odot$ and $M_2 = 0.2M_\odot$ and a period of 41.1 day (Doyle et al. 2011), and Kepler-38b with a planet period of 105.6 day around a stellar binary systems having masses of $M_1 = 0.95M_\odot$ and $M_2 = 0.25M_\odot$ and a period of 18.8 day (Doyle et al. 2011; Orosz et al. 2012).

The idea of a SG planet formation goes back to the first exoplanet detected around a pulsar PSRB1257+12 (Wolszczan & Frail 1992). In this scenario the planet was formed from the material that was ejected in the supernova and formed a disk around the neutron star remnant (Tavani & Brookshaw 1992). Formation of planets in a circum-PCEB disk is currently not understood well, however many circumbinary disks are observed (e.g., Perets 2010 and references therein). Another factor that can help SG planet formation is relevant in the case of AGB post-CE planetary systems, as the ejected material has high metallicity, favoring planet formation under the core accretion scenario (Zorotovic & Schreiber 2013).

Schleicher & Dreizler (2014) studied 12 PCEBs, elaborating on NN Ser, and concluded that in these systems the planets can be formed as SG planets. They give a detailed review on the SG planet formation mechanism (which we will not repeat here; see also Perets 2010), which they found to fit better to the properties of the 12 PCEB systems they have studied. Schleicher & Dreizler (2014) refer to the work of Kashi & Soker (2011) on disk formation in CE evolution. We note however that the post-CE disk mentioned by Kashi & Soker (2011) is much smaller than the proto-planetary disk required in the SG scenario for these systems. Mustill et al. (2013) and Horner et al. (2012) examined the dynamical stability of NN ser and argue that the FG scenario is unlikely, as it is very hard to find a progenitor planetary system for NN Ser that was stable along the evolution. They prefer the SG scenario for NN Ser.

Our interpretation of the literature on the SG formation scenario is that the short timescale available for planet formation supports the disk instability planet formation which is not free of problems either (e.g., Matsuo et al. 2007; Janson et al. 2012). Zorotovic & Schreiber (2013) pointed out that planets will be more likely to form around PCEBs with high mass CO WDs than around low-mass He WDs, as the former are descendants of AGB stars where

the envelope had suffered metal enrichment. Many of the PCEB planets however, are descendants of RGB stars. As for NN Ser, Zorotovic & Schreiber (2013) noted that the cooling age of the WD is on the order of a million years (Parsons et al. 2010a), strongly constraining the SG process.

Motivated by the recent works of Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014) we examine the same twelve systems that Schleicher & Dreizler (2014) have studied, but we concentrate on angular momentum considerations. In section 2 we review the SG scenario in light of angular momentum evolution, and in section 3 we review some constraints on the FG scenario. Our summary and conclusions are in section 4.

2. EXAMINING THE SECOND GENERATION SCENARIO

The systems studied are taken from Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014), and are summarized in Table 1. The first nine columns after the name of each system list observational quantities: (1) primary stellar mass; (2) secondary stellar mass; (3) binary orbital separation; (4, 6, 8) mass, orbital semi-major axis, and eccentricity, of the first planet (not necessarily the inner one); (5, 7, 9) the same for the second planet if exists. The last 5 columns are quantities defined and calculated here: (10) the minimum angular momentum of the planetary system; (11) the initial progenitor mass; (12) the initial angular momentum efficiency factor; (13) the specific angular momentum efficiency factor; (14) our assessment on the likelihood of the SG scenario.

In the 10th column we present our calculation of the minimum angular momentum of the planetary system

$$J_{pm} \equiv \sum \mu_{pj} \sqrt{GM_{tj}(1 - e_{pj}^2)a_j}, \quad (1)$$

where the sum is over the planets $j = 1$ or $j = 1, 2$, μ_{pj} is the reduced mass of planet j , M_{tj} is the total mass inner to the planet including the planet itself, and e_{pj} and a_j are the eccentricity and semi-major axis, respectively, of planet j . It is a minimum angular momentum of the planetary system since the masses of the planets are minimum masses.

In the SG scenario the system starts with the primary and a secondary star. We assume that the secondary star does not change much during the evolution, such that the initial angular momentum of the stellar binary system is given by

$$J_{b0} = \mu_0 \sqrt{GM_0 a_0 (1 - e_0^2)} = 5.9 \left(\frac{\mu_0}{0.13 M_\odot} \right) \left(\frac{M_0}{1.15 M_\odot} \right)^{1/2} \left(\frac{a_0}{2 \text{ AU}} \right)^{1/2} (1 - e_0^2)^{1/2} M_\odot \text{ AU km s}^{-1}, \quad (2)$$

Table 1: Systems - SG Scenario

Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Name	M_1	M_2	a_2	$m_{1p}^{\#1}$	$m_{2p}^{\#1}$	a_{1p}	a_{2p}	e_{1p}	e_{2p}	J_{pm}	$M_{1,0}^{\#3}$	$\eta_{J2}^{\#4}$	$\eta_{L2}^{\#4}$	SG
Units	M_\odot	M_\odot	R_\odot	$M_J^{\#6}$	M_J	AU	AU			$J_s^{\#2}$	M_\odot	$\#7$	$\#8$	$\#9$
Source	Observations ^{#0}									Calculations ^{#5}				
Source	$\#10$									E1		E3	E4	
HW Vir	0.485	0.142	0.857	14.3	30	4.69	12.8	0.4	0.05	3.16	1	0.58	6.8	X
NN Ser	0.535	0.111	0.93	6.91	2.28	5.38	3.39	0	0.2	0.48	2	0.08	12.2	V
QS Vir	0.78	0.43	1.265	9.01	56.59	6.32	7.15	0.62	0.92	2.49	3.5	0.08	3.3	V
RR Cae	0.44	0.183	1.617	4.2		5.3		0		0.23	1	0.03	4.4	V
HS0705	0.483	0.134	3.464	31.5		3.52		0.38		1.25	1	0.25	4.1	X
HS2231 ^{#11}	0.47	0.075	0.789	13.94		5.16				0.69	1	0.23	8.8	X
NSVS	0.46	0.21	0.844	2.8	8	1.9	2.9	0	0.52	0.38	1	0.05	2.4	V
NY Vir ^{#12}	0.459	0.122	0.7585	2.3	2.5	3.3	5.08			0.22	1	0.05	5.3	V
V471	0.84	0.93	3.283	46		12.7		0.26		6.2	3.5	0.1	5.7	?
UZ For	0.71	0.14	0.7846	6.3	7.7	5.9	2.8	0.04	0.05	0.77	3.5	0.07	14.5	V
HU Aqr	0.8	0.18	0.816	7.1		4.3		0.13		0.43	3.5	0.03	12	V
DP Leo ^{#11}	1.2	0.14	0.7266	6.05		8.19		0.39		0.55	6.5	0.04	32.9	V

^{#0} The sources for the observed data are the papers of Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014). For the purpose of this study we do not address the inaccuracies in measurements (for details see Zorotovic & Schreiber 2013).

^{#1} Planets masses are $m_{jp} \sin i$, where $j = 1, 2$ for the two planets and i is the inclination angle of the system.

^{#2} $J_s \equiv M_\odot \text{ AU km s}^{-1}$.

^{#3} The initial mass of the primary star of the massive WDs ($M > 0.55M_\odot$) is based on Claeys et al. (2014); their figure 1. The lighter primaries are assumed to be descendants of solar type stars who terminated their evolution on the RGB. We term them RGBD for RGB descendants. For NN Ser we take $M_{1,0} = 2M_\odot$ (Mustill et al. 2013; Schleicher & Dreizler 2014).

^{#4} η_{J2} and η_{L2} are η_J and η_L , respectively, calculated for $a_0 = 2 \text{ AU}$.

^{#5} Ek stands for equation (k).

^{#6} M_J stands for Jupiter mass.

^{#7} Angular momentum transfer efficiency factor.

^{#8} Specific angular momentum efficiency factor.

^{#9} X means that the SG scenario is unlikely, ? means that the SG scenario is borderline and V means that the SG scenario is possible by angular momentum considerations.

^{#10} More details on specific systems can be found in Guinan & Ribas (2001); Schreiber & Gaumlsnicke (2003); Beuermann et al. (2010); Kilkeny (2011).

^{#11} We note that in both HS 2231 and DP Leo systems M_1 and M_2 are assumed and not derived (for details see Zorotovic & Schreiber 2013 and references within). Therefore the unknowns in these systems are relatively high. In Schleicher & Dreizler (2014) a second options for DP Leo is mentioned (the 13 line in their table 2) due to the high uncertainties we take option 1 for this system (line 12 in table 2 of Schleicher & Dreizler 2014).

^{#12} Note that m_{2p} is assumed and not derived for this system (for more details see Zorotovic & Schreiber 2013).

where, $M_0 = M_{1,0} + M_2$ is the total mass, $M_{1,0}$ and M_2 are the mass of the progenitor and the secondary, respectively, $\mu_0 = M_{1,0}M_2/M_0$ is the initial reduced mass, a_0 is the initial semi-major axis, and e_0 is the initial eccentricity; we will assume initial circular orbits.

We can consider three types of systems according to the primary present mass.

(a) Systems that have a primary of $M_1 < 0.55M_\odot$. These are descendants of interaction on the RGB. For these we assume an initial primary mass of $1M_\odot$, based on the initial-final mass relation given by Claeys et al. (2014)). We note that Zorotovic & Schreiber (2013) take $M_{1,0} \simeq 1.2M_\odot$. However, the typical mass of the secondary star in their study is $\sim 0.6M_\odot$, while the typical mass of the observed secondary stars is $M_2 \simeq 0.15M_\odot$. Therefore, for RGB descendant (RGBD) primaries we take $M_{1,0} =$ (see remark #3 in Table 1).

(b) Systems where the primary remnant is a massive WD, $0.7 < M < 0.85M_\odot$, that was the core of an AGB star. For these we take the initial primary mass to be $3.5M_\odot$, based on the relation given by Claeys et al. 2014).

(c) One system, DP Leo, has a very massive WD remnant of $\sim 1.2M_\odot$, that is likely to be a descendant of a massive AGB star. This mass is assumed rather than derived accurately (for details see Zorotovic & Schreiber 2013 and references therein). For this system we take the initial primary mass to be $6.5M_\odot$. For such a massive WD, the system avoids the CE phase on the RGB, but in our proposed scenario tidal interaction increases mass-loss and therefore orbital separation increases before the AGB phase.

Our estimated values of $M_{1,0}$ are listed in Table 1 (column 11). The strongest constrain we derive below on the SG scenario comes from RGBD. On the RGB the star reaches a maximum radius of $\sim 0.5 - 1$ AU, and tidal interaction can bring a companion from a distance of up to $a_0 \sim 4R$ (Soker 1996). We therefore take the initial orbital separation of the primary and secondary to be $a_0 = 2$ AU. This is more or less a maximum initial separation; the average will be lower.

We now define two efficiency parameters. The first one is the fraction of initial angular momentum that ends in the planetary system according to the SG scenario, η_J

$$\eta_J = \frac{J_{pm}}{J_{b\delta}}; \quad \eta_{J2} \equiv \eta_J(a_0 = 2AU). \quad (3)$$

Here, $J_{b\delta}$ is defined as the difference between the initial and final angular momentum according to the SG planet formation scenario: $J_{b\delta} = J_{b0} - J_{bf}$, where J_{bf} is the final angular momentum of the inner stellar binary system, and J_{b0} is given by equation 2. In many scenarios for planet formation a small fraction of < 0.1 of the mass in the proto-planetary disk ends up in planets (e.g., Alibert et al. 2005; Alexander et al. 2013). In the SG scenario studied here, even if all the envelope mass ends up in the proto-planetary disk, we expect that only $\lesssim 0.1$ of the initial disk mass, hence angular momentum, will end up in the planets.

As some envelope mass will be lost in the wind rather through the proto-planetary disk, we expect that a lower fraction, $\eta_J < 0.1$, of the initial angular momentum will end in the planets.

The second efficiency parameter is based on the specific angular momentum. It is defined as the ratio of the angular momentum that ended in the planetary system per unit mass of the planets, $j_{pm} = J_{pm}/m_p$, where $m_p = m_{1p} + m_{2p}$, to that of the entire ejected envelope (again, a minimum value is given to the angular momentum of the planetary system). The value of j_{pm} , defined for the observed planets, is about equal to the angular momentum per unit mass of the disk from which the planets have been formed. The envelope mass lost is $M_{\text{env}} = M_{1,0} - M_1$. This specific angular momentum efficiency factor is introduced by Schleicher & Dreizler (2014) as α_L where they assumed that $\alpha_L \sim 10$. Namely, an enhancement of an order of magnitude in specific angular momentum between that of the primary envelope and the proto-planetary disk is required. Since Schleicher & Dreizler (2014) calibrated α_L and we calculate it, we use a different notation η_L which is given by

$$\eta_L = \frac{j_{pm}}{(J_{b\delta})/M_{\text{env}}} \simeq \frac{\eta_J}{m_p/M_{\text{env}}}; \quad \eta_{m2} \equiv \eta_m(a_0 = 2 \text{ AU}). \quad (4)$$

If, for example, the entire envelope of the primary ends in the disk then $\eta_L \simeq 1$.

We can crudely estimate the value η_L in a simple model where we assume that the proto-planetary disk in the SG scenario is formed by mass lost through the second lagrangian point L_2 . The ratio of specific angular momentum in the envelope to that lost from L_2 is

$$\eta_L \sim \frac{\omega r_{L_2}^2}{\xi \omega R_g^2}, \quad (5)$$

where $\xi M_{\text{env}} R_g^2$ is the moment of inertia of the primary envelope, and ω is the angular velocity of both the primary envelope and the binary system, as we assumed synchronized orbit. R_g is the radius of the primary which is a giant star. Substituting typical values of the parameters we obtained

$$\eta_L \sim 20 \left(\frac{r_{L_2}}{2R_g} \right)^2 \left(\frac{\xi}{0.2} \right)^{-1}. \quad (6)$$

Examining column 13 of Table 1 we find that there is no problem for the SG scenario with regards to the high specific angular momentum in the proto-planetary disk.

We can divide the systems into three groups according to the constraints from angular momentum considerations.

1. Systems where $\eta_{J2} < 0.1$ (marked ‘V’ in column 14 in Table 1). In these system the efficiency factors imply that binary system had sufficient initial angular momentum to

account for the formation of a proto-planetary disk and planets, under the assumption that not less than ~ 0.1 of the disk mass ended up in forming the planets.

2. Systems where $\eta_{J2} \sim 0.1$ (marked ‘?’ in column 14 in Table 1). In these systems the efficiency factors imply that the SG scenario might be possible, although the transfer of gas from the proto-planetary disk to the planets must be very efficient. Other considerations should be taken into account. For example, in the case of NN Ser dynamical instabilities (e.g., see Völschow et al. 2014) might make the SG scenario more likely than the FG scenario.
3. Systems where $\eta_{J2} > 0.2$ (marked ‘X’ in column 14 in Table 1). In these systems a very large fraction of > 0.2 of the proto-planetary disk must end up in planets. This is a large fraction considering the view on planet formation (Alexander et al. 2013). Therefore planets will probably not be formed by the SG planet formation scenario in these systems.

From angular momentum considerations the SG scenario has difficulties with about 25% of the systems, This assessment is based on present planet formation models that take a fraction of < 0.1 of the proto-planetary mass to end up in forming planets (Alexander et al. 2013). However, none of the systems has a planetary system angular momentum larger than the estimated initial angular momentum of the binary system. This might be a rescue wheel for the SG scenario.

As can be seen from Table 1 the planets orbital separations around the studied PCEBs ($a < 10$ AU) disagree with the predictions of the disk instability model ($a > 20$ AU for more details see Boss 2011; Zorotovic & Schreiber 2013). As noted by Zorotovic & Schreiber (2013) migration (Beuermann et al. 2013) and/or scattering can explain this phenomenon. However, as pointed out by Zorotovic & Schreiber (2013) it seems that SG disks are highly unstable, fragment and tend to form giant planets, while disks around young single stars and MS binaries only form planets in ~ 0.1 of the cases. The high frequency of planets around PCEB (Zorotovic & Schreiber 2013) and the short time scale of the SG planet formation can result from the enhanced dust to gas mass ratio as claimed by Zorotovic & Schreiber (2013). However, this enhancement does not exist in He WDs. Zorotovic & Schreiber (2013) suggest that enrichment in PCEBs with sdB might occur very close to the tip of the RGB (for more details see Boyer et al. 2010).

3. THE FIRST GENERATION SCENARIO

To evaluate the FG scenario we calculate the factor η_{ML} by which the orbital separation of the planets increase due to mass-loss

$$a_{jp,0} = \eta_{\text{ML}} a_{jp} = \frac{M_1 + M_2 + \sum m_{jp}}{M_{1,0} + M_2 + \sum m_{jp}} a_{jp}, \quad (7)$$

where m_{jp} is the mass of the planet, and the sum is over the planets $j = 1$ or $j = 2$. The second equality defines the mass-loss factor η_{ML} , and we assume that the mass of the secondary star and planets did not change along the evolution. The initial orbital separations of the planets calculated by equation (7) are presented in columns 8 and 9 in Table 2. The other quantities listed in Table 2 are, according to their columns, as follows. (1-2) the primary and secondary masses, as in Table 1; (3) the estimated progenitor mass as column 11 in Table 1; (4-7) the planetary masses and period (Table 1); (10) the resonance between the planets periods; (11) the initial orbital separation of the stellar binary system assuming a 1:2 resonance between the secondary and the inner plan periods.

We further note that there are resonances between the orbital periods of planets (column 10 in Table 2). Some of this resonances have been reported previously (e.g., NN Ser, Beuermann et al. 2013). To be able to proceed, we make the assumption that in the initial system, before the primary left the MS, the secondary star and the inner planet were in a resonance and we take it to be a 1:2 resonance. This might make the system stable, and allow us to build the scenario discussed below. A resonance of 2:3, as Neptune and Pluto have for example, will move the initial orbit of the secondary star a little outward, and will not change the proposed scenario. In systems where the initial secondary orbital separation is ≥ 1 AU, we can allow according to our proposed scenario the secondary to have a lower initial orbital separation, e.g., to be 0.63 times the orbital separation given in Table 2 and have a 1:4 resonance with the inner planet.

The proposed scenario for all systems is based on a strong tidal interaction during the RGB phase, for the RGBD systems (i.e., primaries that are descendants of RGB stars: He WD, horizontal branch stars, or CO WDs that are descendants of HB stars). However, an early CE phase is avoided because the secondary star is massive enough to bring the system to synchronization between the rotation of the primary envelope and the orbital motion of the secondary star. A CE phase occurs only later, on the late RGB for the RGBD progenitors, and on the late AGB phase for the CO (or ONeMg) WD progenitors.

We consider the following scenario for the RGBD systems. The progenitors of these stars, assumed to be $M_{1,0} \sim 1M_{\odot}$ on the MS, expand up to $\sim 200R_{\odot} \simeq 1$ AU on their RGB (e.g., Iben & Tutukov 1985). From our estimated initial orbital separation of the secondary

Table 2: Systems - FG Scenario

Column	1	2	3	4	5	6	7	8	9	10	11
Name	M_1	M_2	$M_{1,0}$	m_{1p}	m_{2p}	P_{1p}	P_{2p}	$a_{1p,0}$	$a_{2p,0}$	$P_{1p,0} : P_{2p,0}^{*2}$	a_0^{*1}
units	M_\odot	M_\odot	M_\odot	M_J	M_J	yr	yr	AU	AU		AU
Source	Observations ^{*0}	Assumed	Observations ^{*0}				Calculations				Assumed
HW Vir	0.485	0.142	1	14.3	30	12.7	55	2.60	7.24	2:9	1.63
NN Ser	0.535	0.111	2	6.91	2.28	15.5	7.75	1.65	1.05	(1.05)3:2	0.66
NN Ser ^{*3}	0.535	0.111	1	6.91	2.28	15.5	7.75	3.14	1.98	2:1	1.25
QS Vir	0.78	0.43	3.5	9.01	56.59	14.4	16.99	1.96	2.28	4:5	1.23
RR Cae	0.44	0.183	1	4.2		11.9		2.80			1.76
HS0705	0.483	0.134	1	31.5		8.41		1.96			1.22
HS2231	0.47	0.075	1	13.94		15.7		2.65			1.66
NSVS	0.46	0.21	1	2.8	8	3.49	6.86	1.05	1.62	(1.06)1:2	0.66
NY Vir	0.459	0.122	1	2.3	2.5	7.9	15	1.71	2.64	(1.05)1:2	1.08
V471	0.84	0.93	3.5	46		33.2		5.15			3.23
UZ For	0.71	0.14	3.5	6.3	7.7	16	5.25	1.39	0.66	3:1	0.42
HU Aqr	0.8	0.18	3.5	7.1		9		1.15			0.725
DP Leo	1.2	0.14	6.5	6.05		28.01		1.66			1.04

*0 The sources for the observed data are the papers of Zorotovic & Schreiber (2013) and Schleicher & Dreizler (2014). For the purpose of this study we do not address the inaccuracies in measurements (for details see Zorotovic & Schreiber 2013).

*1 The initial orbital separation of the secondary star is calculated under the assumption of a stable resonance of 1:2 of the secondary (M_2) with the closest planet.

*2 The resonance are calculated as $\frac{P_{1p,0}}{P_{2p,0}}$. If the deviation from the written two integers ratio is larger than 2% we indicate the factor of deviation in the parenthesis.

*3 We show two options for NN Ser. The first line assumes $M_{1,0} = 2M_\odot$ (Mustill et al. 2013; Schleicher & Dreizler 2014) and the second line assumes $M_{1,0} = 1M_\odot$.

stars, last column in Table 2, we see that a strong tidal interaction takes place during the RGB phase of the primary. The secondary brings the primary envelope to synchronization with the orbital motion, and a CE phase is avoided as interaction starts. The primary RGB star loses mass and expands as its core’s mass grows, and eventually a CE phase is unavoidable. However, by this stage the envelope mass is lower than its initial value, and the secondary star survives the CE phase despite its low mass. The planets move outward due to the mass-loss process. The mass-loss process during the CE phase can be on a time scale shorter than the planets’ orbital period, which can explain the non-zero eccentricity in some cases.

Stars starting with a mass of $M_{1,0} \gtrsim 2.3M_{\odot}$ on the MS expand much less during their RGB phase (e.g., Iben & Tutukov 1985). Therefore, the scenario plotted above for the RGBD systems occurs also for the more massive WD systems, but during the AGB phase of the primary star. These estimations are in accordance with Zorotovic & Schreiber (2013) who noted that the range in orbital separation in the initial binary is ~ 0.5 AU to ~ 2.5 AU depending on the final mass of the primary.

In DP Leo the progenitor of the massive WD was most likely a massive star of $\gtrsim 6M_{\odot}$ on the MS. How did the a secondary star of mass $M_2 = 0.14M_{\odot}$ survived the CE phase in a massive envelope of such a primary star? If the secondary star was formed as a planet does, as we suggest in the present study, it is plausible that an even inner body, a massive planet or a brown dwarf, was presence in the system. This inner body entered the envelope of the primary at an earlier stage and did not survive its CE phase. But as it spiraled-in and collided with the primary core it ejected a large fraction of the primary envelope. This enabled the secondary star to survive its CE phase (Bear & Soker 2011), now taking place in a much lighter envelope

The low mass of the secondary stars in most studied PCEBs deserve some attention. Zorotovic & Schreiber (2013) performed a binary population study of these PCEBs to characterize their main sequence binary progenitors. The average secondary mass in their population synthesis study was $\sim 0.6M_{\odot}$, much larger than the value in most systems studied here. This large discrepancy might hint that the secondary was not formed as a star forms, but rather like massive planets form.

Another aspect of the low-mass secondary stars are the way they interact with the evolving primary star. They are not sufficiently massive to eject the primary envelope before they spiral deeply in, but they are massive enough to bring the envelope to synchronization before they enter the CE phase. After the primary envelope spin is synchronized with the orbital motion, a Darwin instability might occur. The instability sets in when the moment of inertia of the primary envelope $\xi M_{\text{env}} R_g^2$ exceeds third of the orbital moment of inertia,

$\sim M_2 a^2$, where a is taken at synchronization. The condition for instability to occur reads

$$M_2 \leq 0.3 \left(\frac{\xi}{0.2} \right) \left(\frac{M_{env}}{0.5 M_\odot} \right) \left(\frac{R_g}{a} \right)^2 M_\odot \quad (8)$$

For orbital separation at synchronization of $R_g < a \lesssim 2R_g$ the condition for instability to occur is $M_2 \lesssim 0.075 - 0.3 M_\odot$. This shows that the secondary stars in most system will enter the envelope due to Darwin instability. This, we argue, what makes these systems unique.

Finally we note that even in the FG scenario the already existing planets can accrete some of the mass lost by the stellar binary system (e.g., Perets 2010; Beuermann et al. 2013; Zorotovic & Schreiber 2013; Schleicher & Dreizler 2014). In this hybrid scenario the low-mass planets can be treated as "seeds" that can accrete more mass from the disk. The mass accretion can reduce orbital separation of planets. This hybrid scenario can bridge between the FG scenario and the SG scenario. However, in most systems we find that the FG scenario can work without the aid of mass accretion.

4. SUMMARY

We compared the the second generation (SG) planet formation scenario with the first generation (FG) planet formation scenario for twelve post common envelope binary (PCEB) systems that host planets. We concentrated on constraints imposed from angular momentum evolution. In comparing the FG with SG scenarios one should examine what is more likely, and whether one of the possibilities can be ruled out. Doing that, we reach the following conclusions.

1. When considering the SG scenario we find that in none of the PCEBs the planetary system angular momentum is larger than the estimated initial stellar binary angular momentum. However, in three systems (marked X in the last column of Table 1), our calculated efficiency of angular momentum transfer from the stellar binary system to the planetary systems is extremely high, $\eta_{J2} > 0.2$. It implies that more than 20% of the proto-planetary disk mass in these three systems ended up in planets. This is a very high efficiency (Alexander et al. 2013) that imposes strong challenge to the SG scenario.
2. We found that all planets in the twelve systems can be FG planets. However, when the primary was a main sequence (MS) star, the planets were closer to the center; they moved outward during evolution due to mass-loss. The secondary star, on the other hand, had to be at an orbital separation of $\gtrsim 0.5$ AU to allow the primary

to develop a massive core. Hence, the orbits of the secondary star and of the inner planet were quite close to each other in many systems, according to the FG scenario. To maintain such close orbits requires that in such systems the orbit of the stellar companion and the inner planet were in a resonance. A support to the presence of a resonance is the resonance that exists today between the two planets in many of the systems (columns 6 and 7 in Table 2). For that, in estimating the initial stellar binary orbital separation we assumed a resonance of 1:2 between the secondary and the inner planet (column 11 in Table 2). Resonances similar to the ones assumed here are present in many exoplanet systems between the planets (e.g., Marcy et al. 2005; Tinney et al. 2006; Raymond et al. 2008; Gozdziewski & Migaszewski 2013)

3. Following the previous conclusion, in the FG scenario it is quite likely that the secondary star was formed as a planet, but accreted mass from the proto-planetary disk of the young star, as it is not easy to form planets around binary stars (e.g., Lines et al. 2014).

Overall, we consider the FG scenario more likely, at least from angular momentum considerations. Although Schleicher & Dreizler (2014) and Zorotovic & Schreiber (2013) conclude that the SG scenario is more likely, they also hint that some systems can form through the FG scenario. We note that other aspects (e.g., stability, typical lifetime) should be incorporated in the model for a better understanding of the overall picture. In some of the systems FG planets might accrete mass. Such a process can enrich the outcome of PCEB evolution. Additionally, the existence of a low-mass body closer even to the center than the stellar companion in the progenitor system can help the stellar binary survive the evolution. It does so by increasing the mass lost from the primary prior to the entrance of the secondary star to the primary envelope.

We note that many other PCEB systems are known. Currently many of them are not known to host planets (Schreiber & Gaumliniscke 2003; Zorotovic & Schreiber 2013; Schleicher & Dreizler 2014). These systems might be good candidates for planet observations. Furthermore, Schaffenroth et al. (2014) recently discovered a PCEB where the primary has a mass of $M_1 = 0.47M_\odot$ and the companion is a brown dwarf of mass $M_2 = 0.064M_\odot$. This brown dwarf survived the CE phase and probably triggered the mass-loss process that transformed the progenitor of the primary to a sdB star. Today observations point out that the primary masses of PCEBs with planets exclude $M_1 \sim 0.6M_\odot$. The lack of this typical range in mass in PCEBs where planets have been found is probably the result of the evolutionary process. Further research on this topic is required.

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